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Johannessen

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(54) THERMAL COMPENSATION OF WAVEGUIDES BY DUAL MATERIAL CORE HAVING POSITIVE THERMO-OPTIC COEFFICIENT INNER CORE

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(22) Filed: **Jul. 2, 2002**

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(51) **Int. Cl.**
G02F 1/295 (2006.01)

(52) **U.S. Cl.** **385/8**; 385/14; 385/16; 385/17; 385/27; 385/40; 385/129

(58) **Field of Classification Search** 385/3, 385/18, 16, 40–45, 123–130, 144–147, 14, 385/12
See application file for complete search history.

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Assistant Examiner—David A. Vanore
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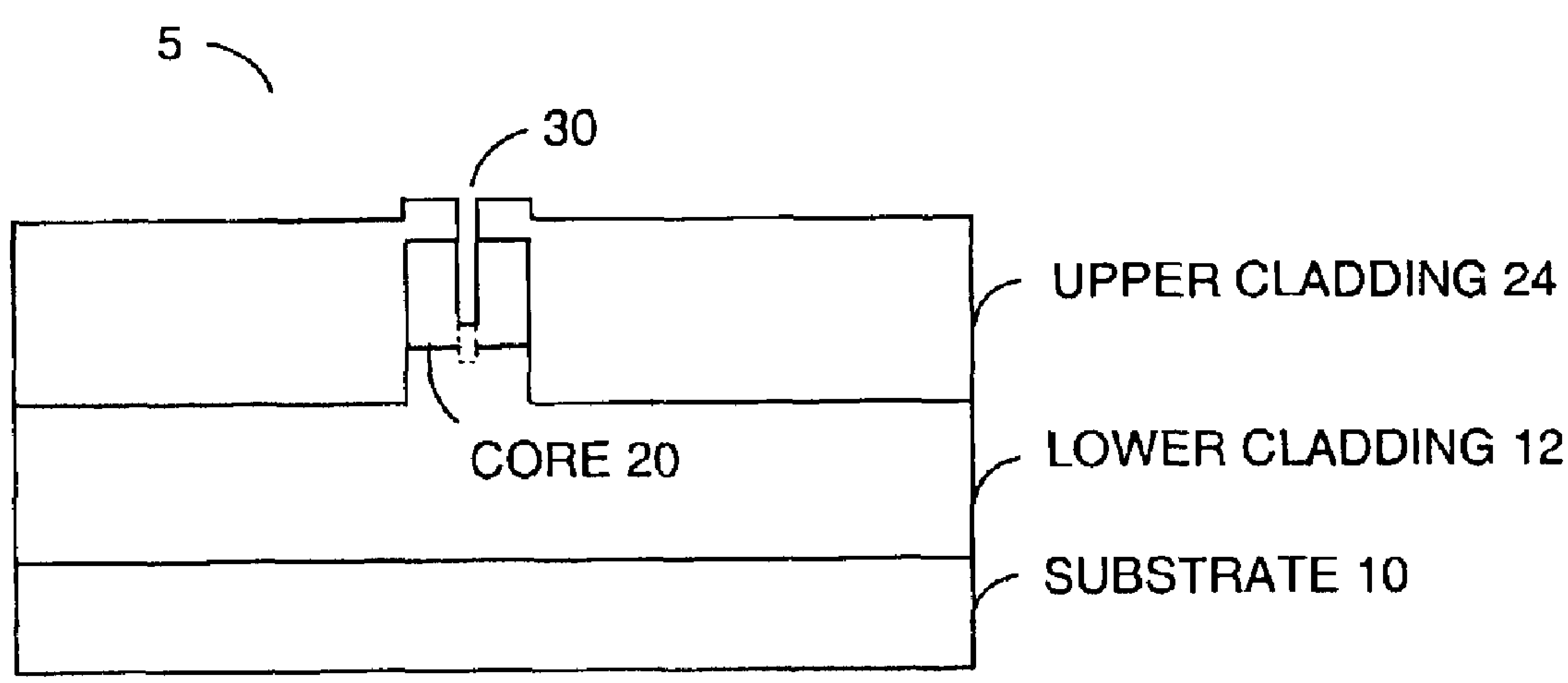
(57) **ABSTRACT**

A planar lightwave circuit comprises a waveguide that is thermally-compensating. The waveguide comprises a cladding and a core that comprises two regions running lengthwise through the core. One region has a negative thermo-optic coefficient; the other region has a positive thermo-optic coefficient.

25 Claims, 8 Drawing Sheets



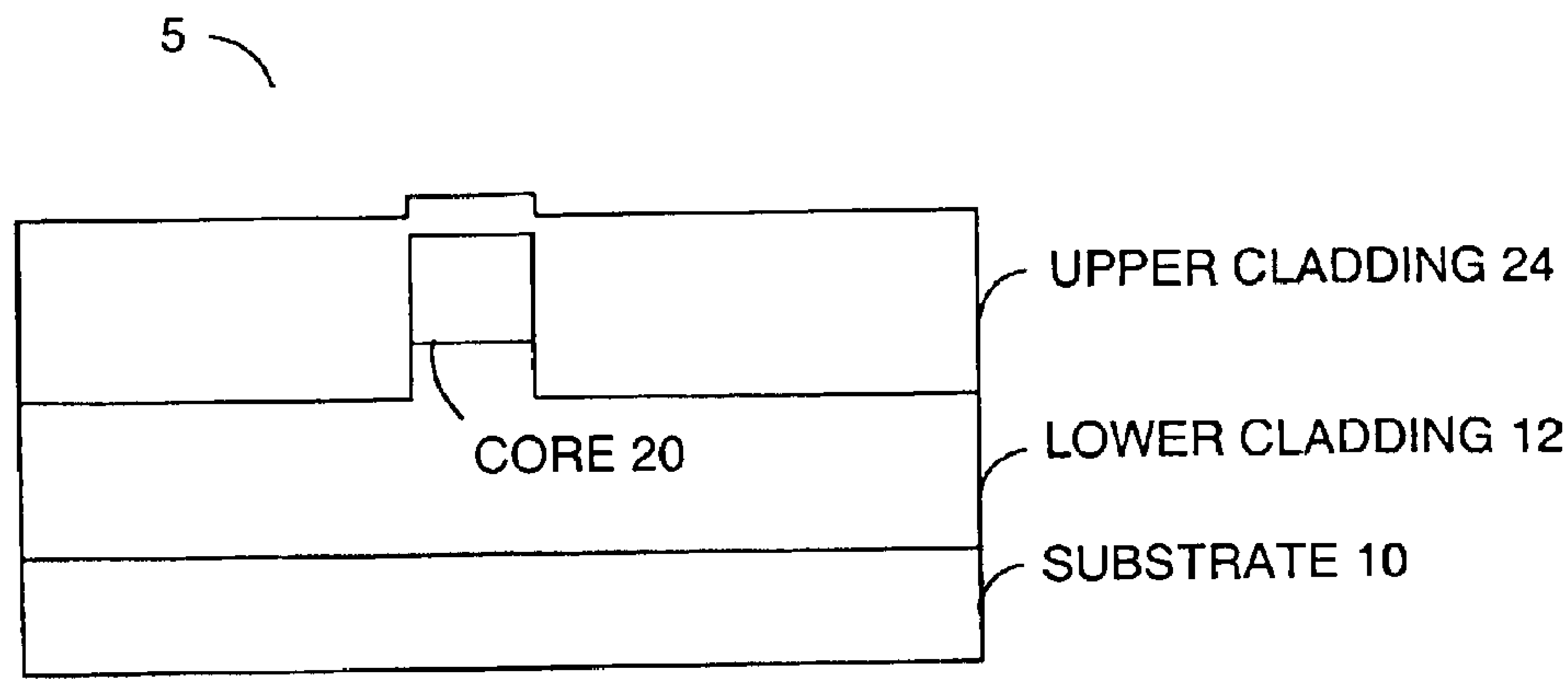

5
UPPER CLADDING 24
CORE 20
LOWER CLADDING 12
SUBSTRATE 10

FIG. 1A

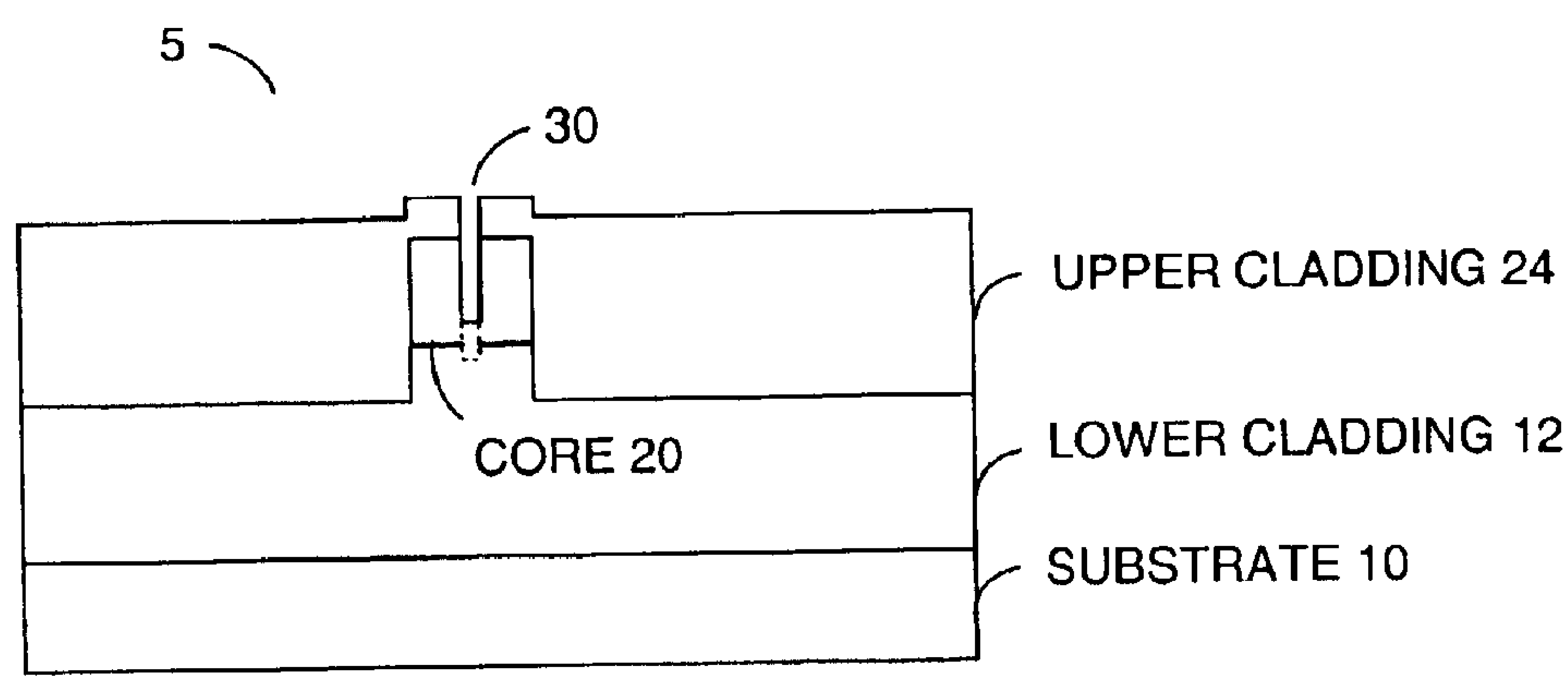

5
30
UPPER CLADDING 24
CORE 20
LOWER CLADDING 12
SUBSTRATE 10

FIG. 1B

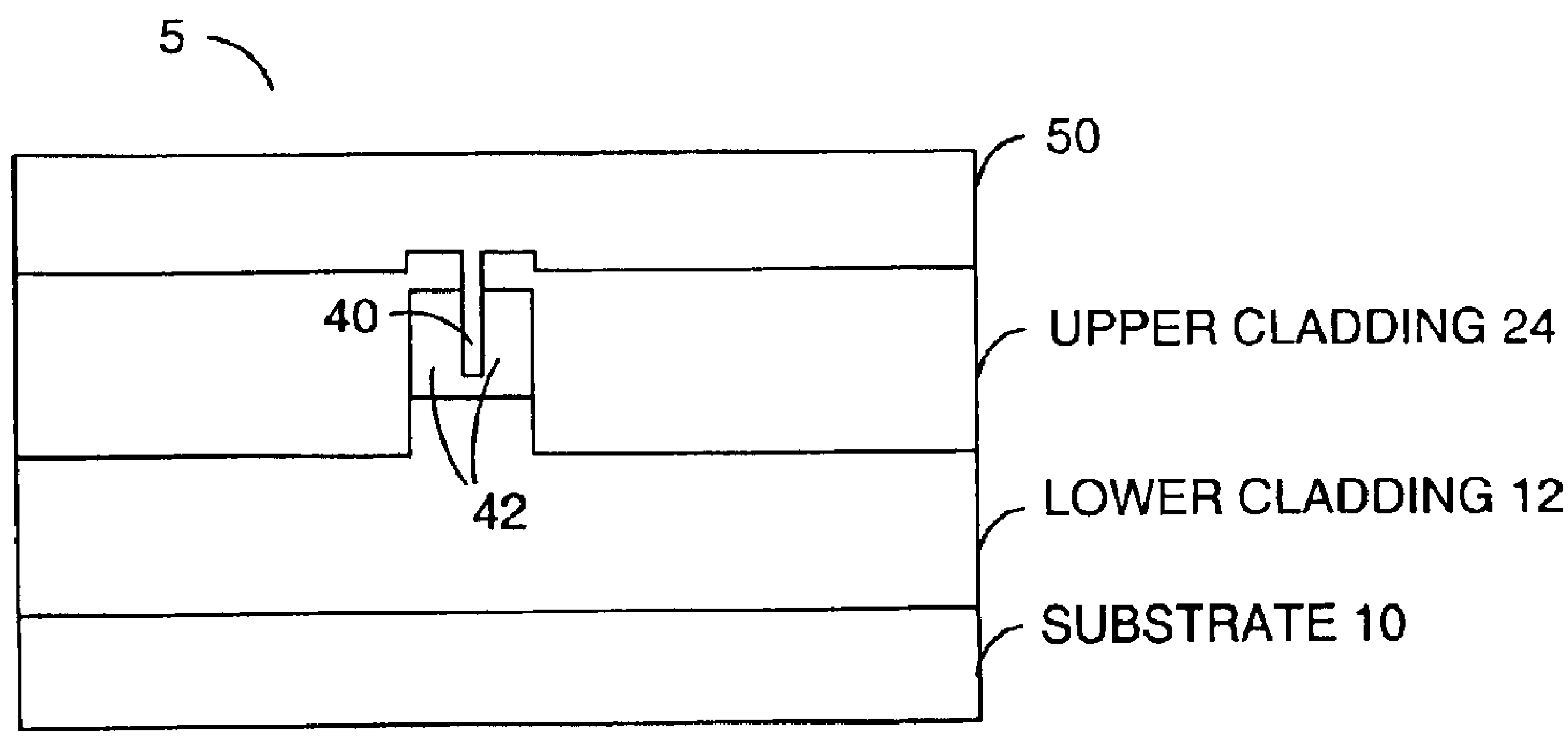


FIG. 1C

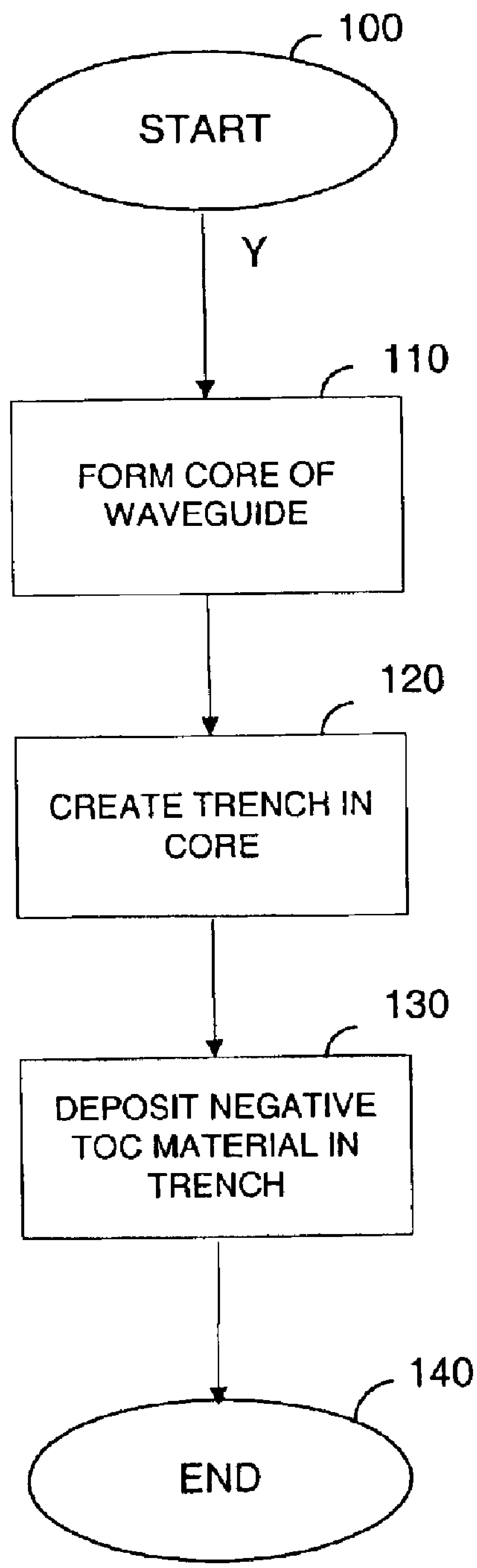

100
START
Y
110
FORM CORE OF WAVEGUIDE
120
CREATE TRENCH IN CORE
130
DEPOSIT NEGATIVE TOC MATERIAL IN TRENCH
140
END

FIG. 2

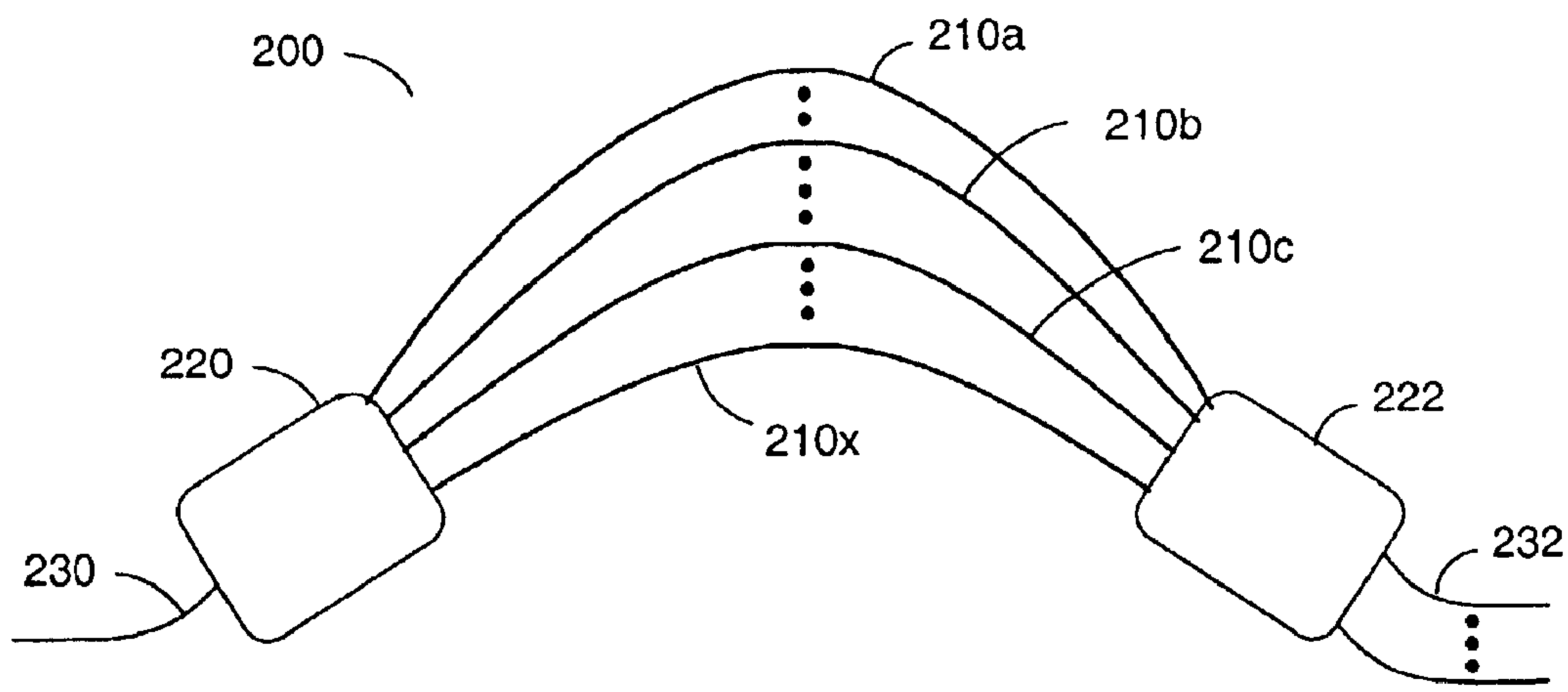

200
210a
210b
210c
220
222
210x
230
232

FIG. 3

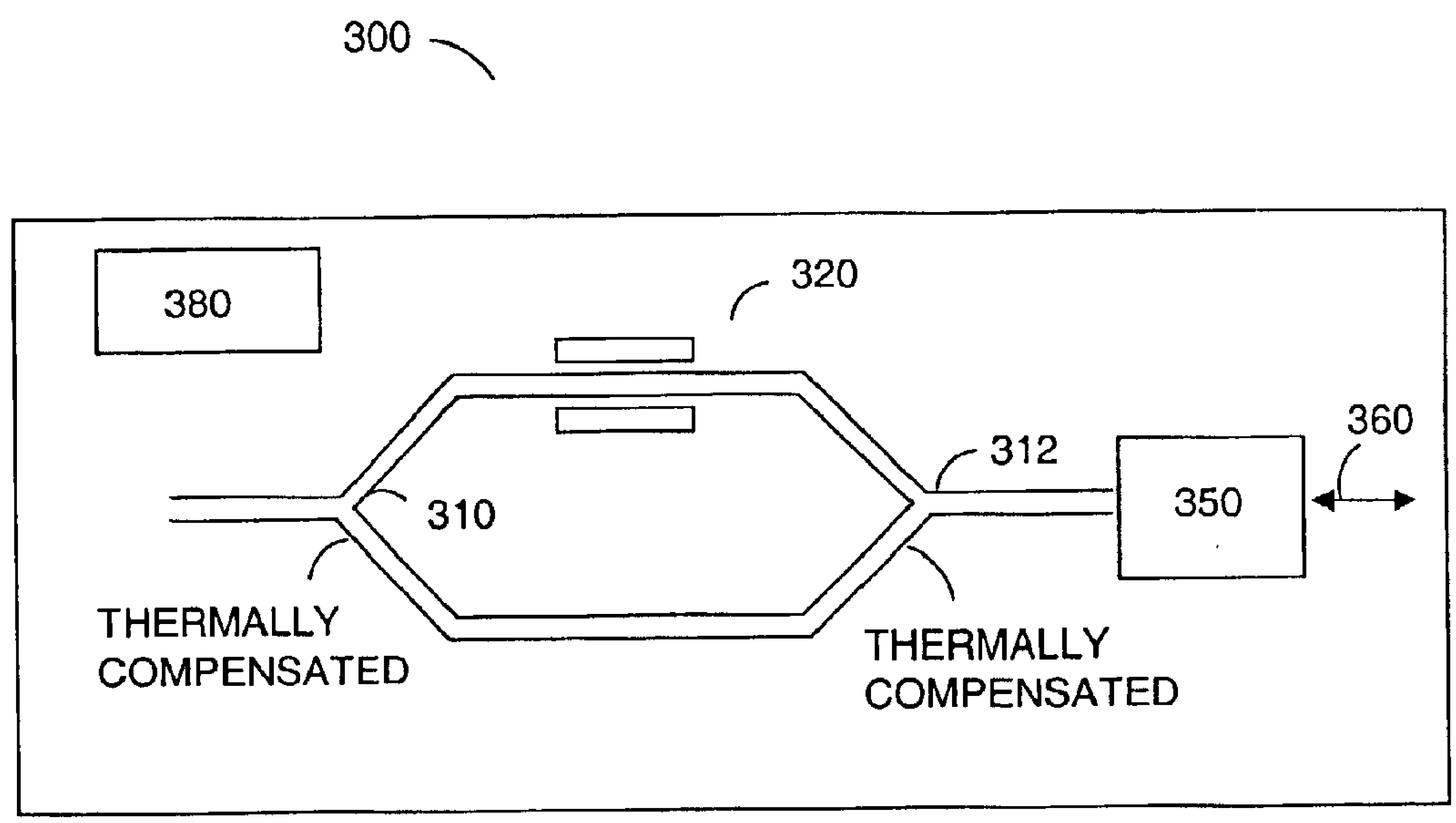

300
380
320
360
312
310
350
THERMALLY
COMPENSATED
THERMALLY
COMPENSATED

FIG. 4

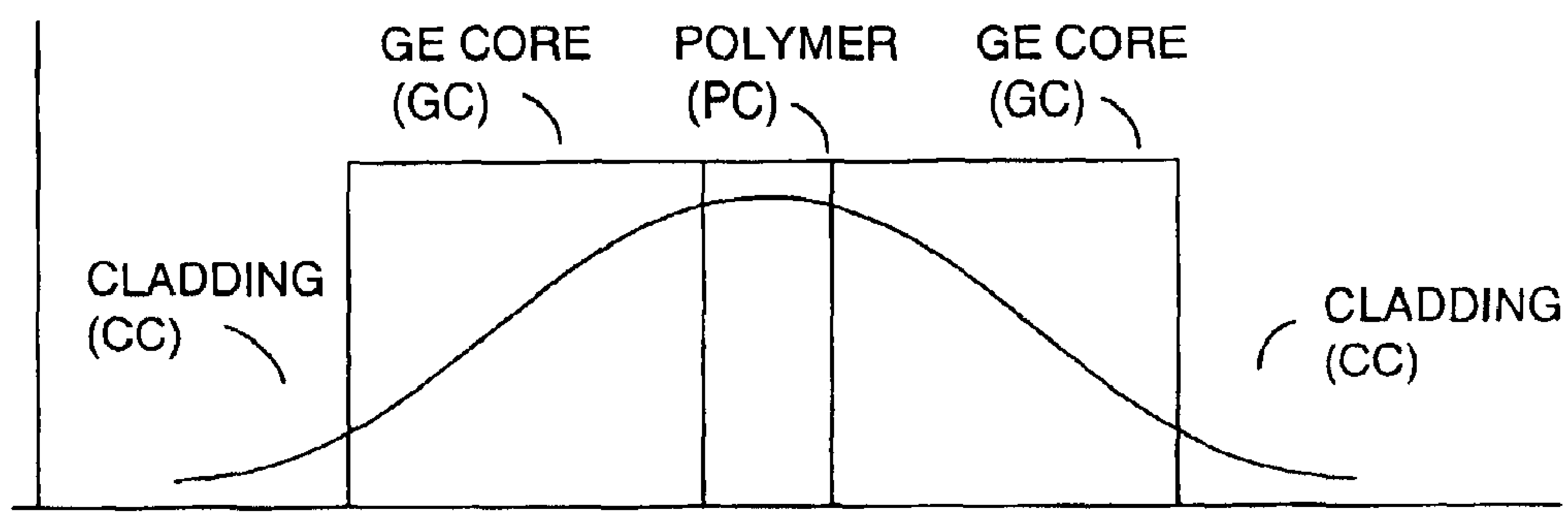

GE CORE
(GC)
POLYMER
(PC)
GE CORE
(GC)
CLADDING
(CC)
CLADDING
(CC)

FIG. 5

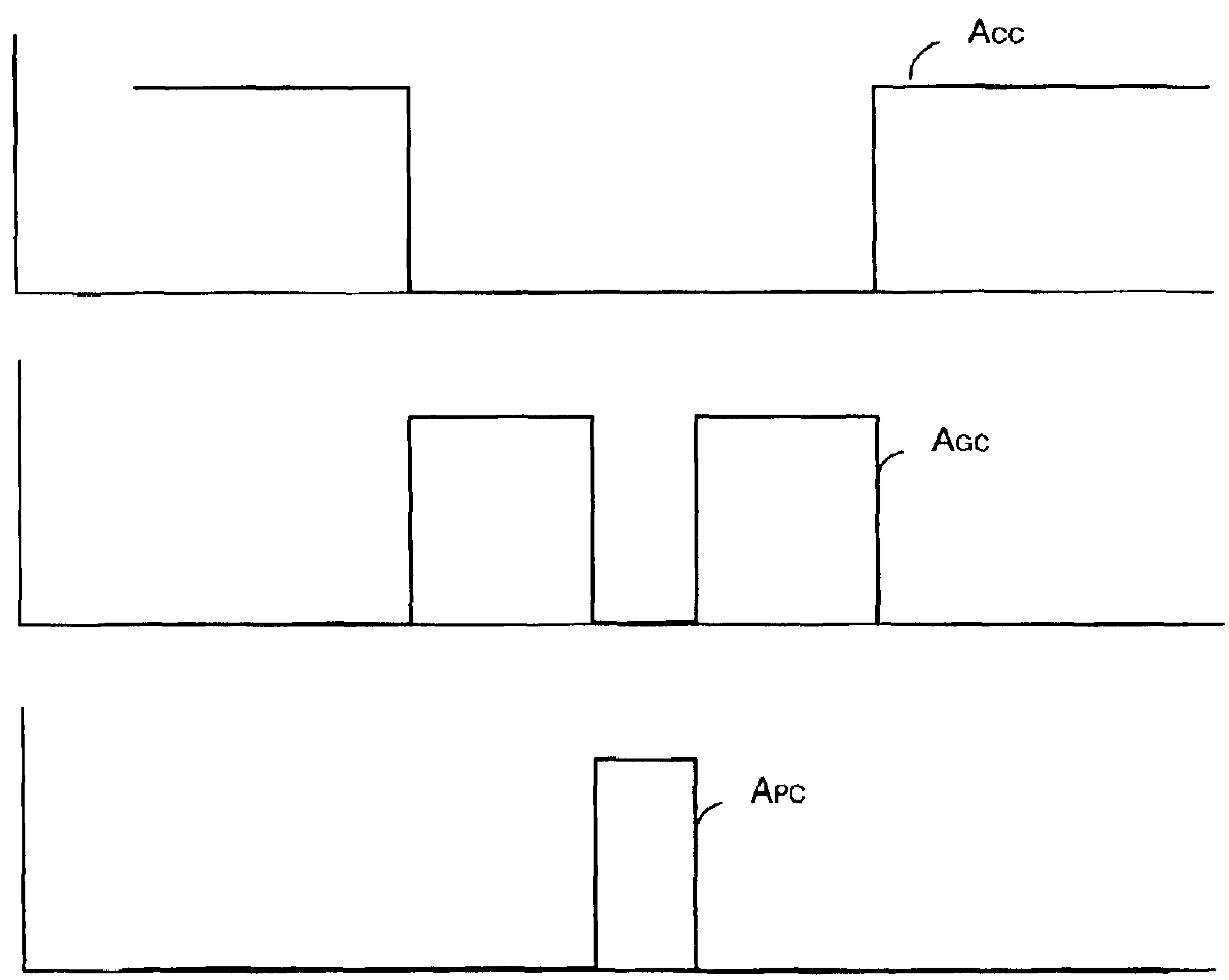

ACC
AGC
APC

FIG. 6

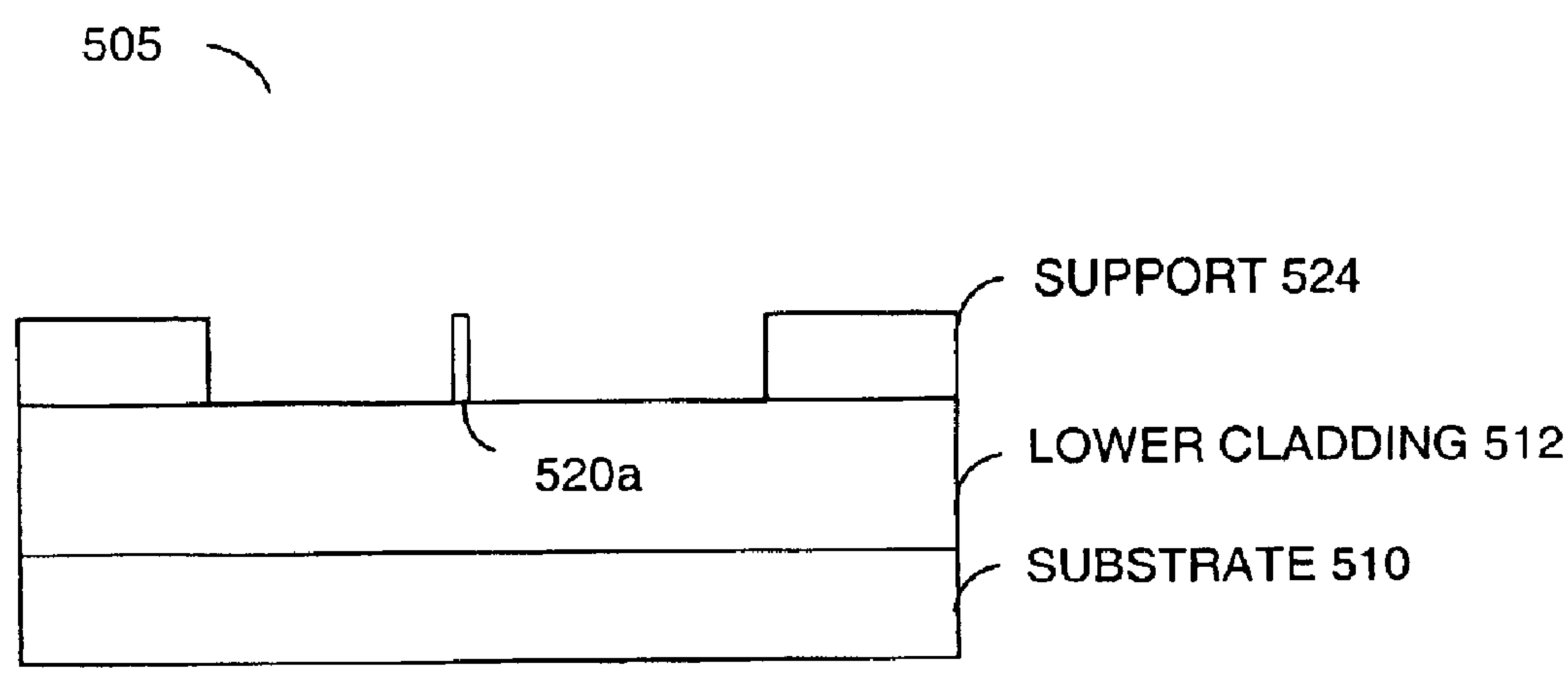

505
SUPPORT 524
LOWER CLADDING 512
SUBSTRATE 510
520a

FIG. 7A

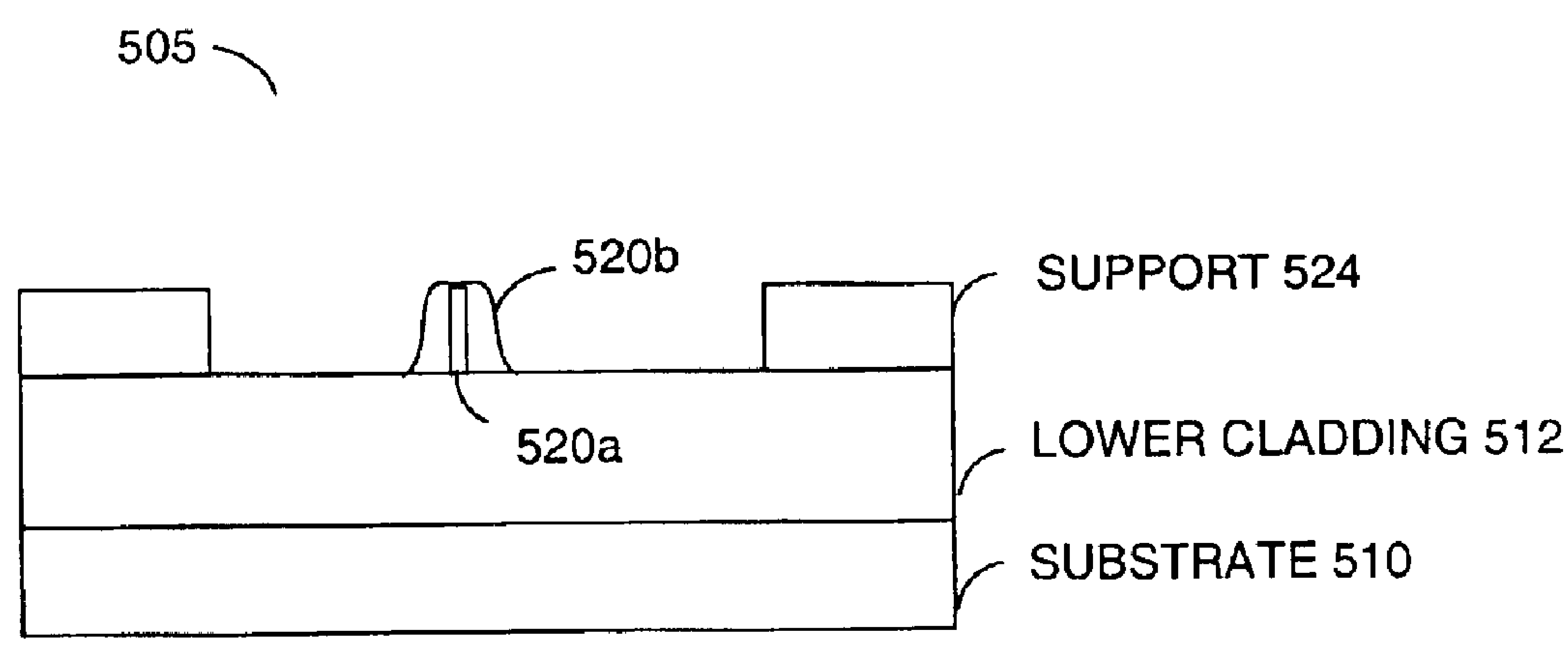

505
520b
SUPPORT 524
520a
LOWER CLADDING 512
SUBSTRATE 510

FIG. 7B

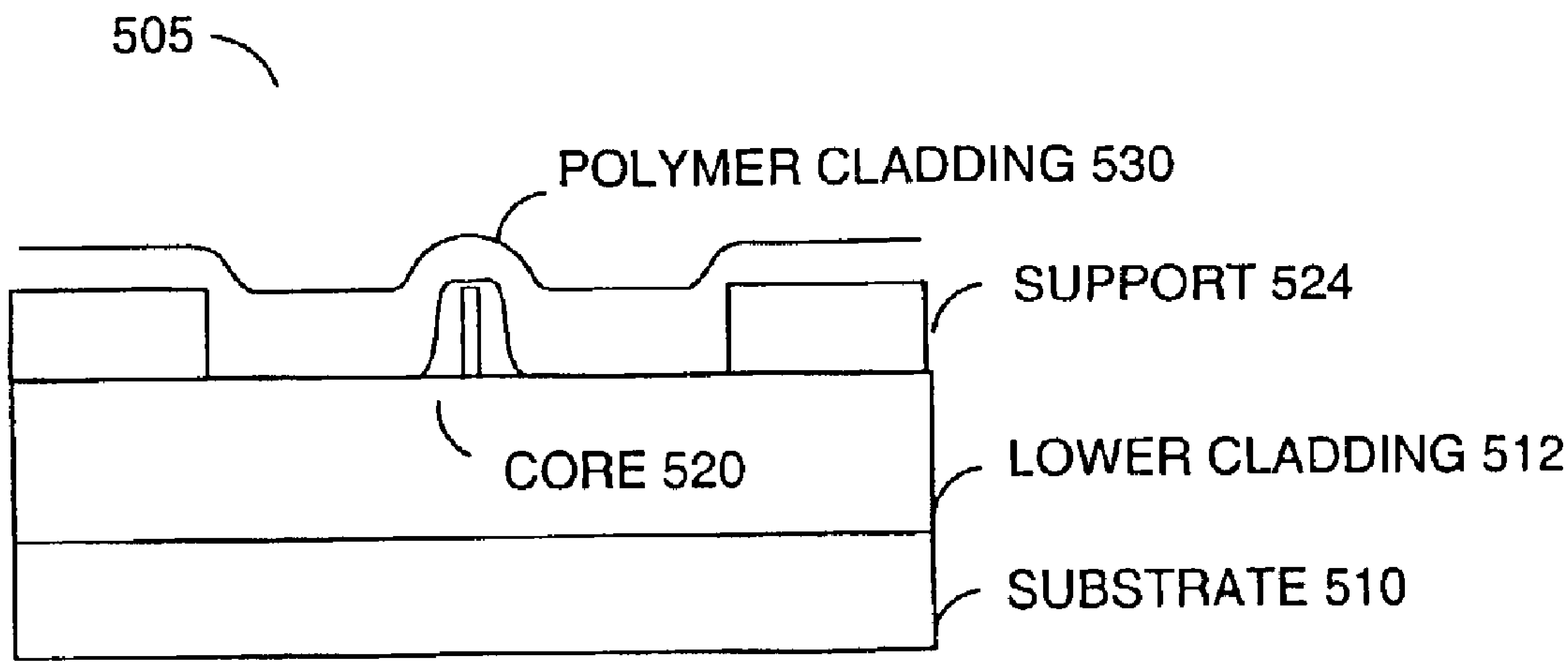

505
POLYMER CLADDING 530
SUPPORT 524
CORE 520
LOWER CLADDING 512
SUBSTRATE 510

FIG. 7C

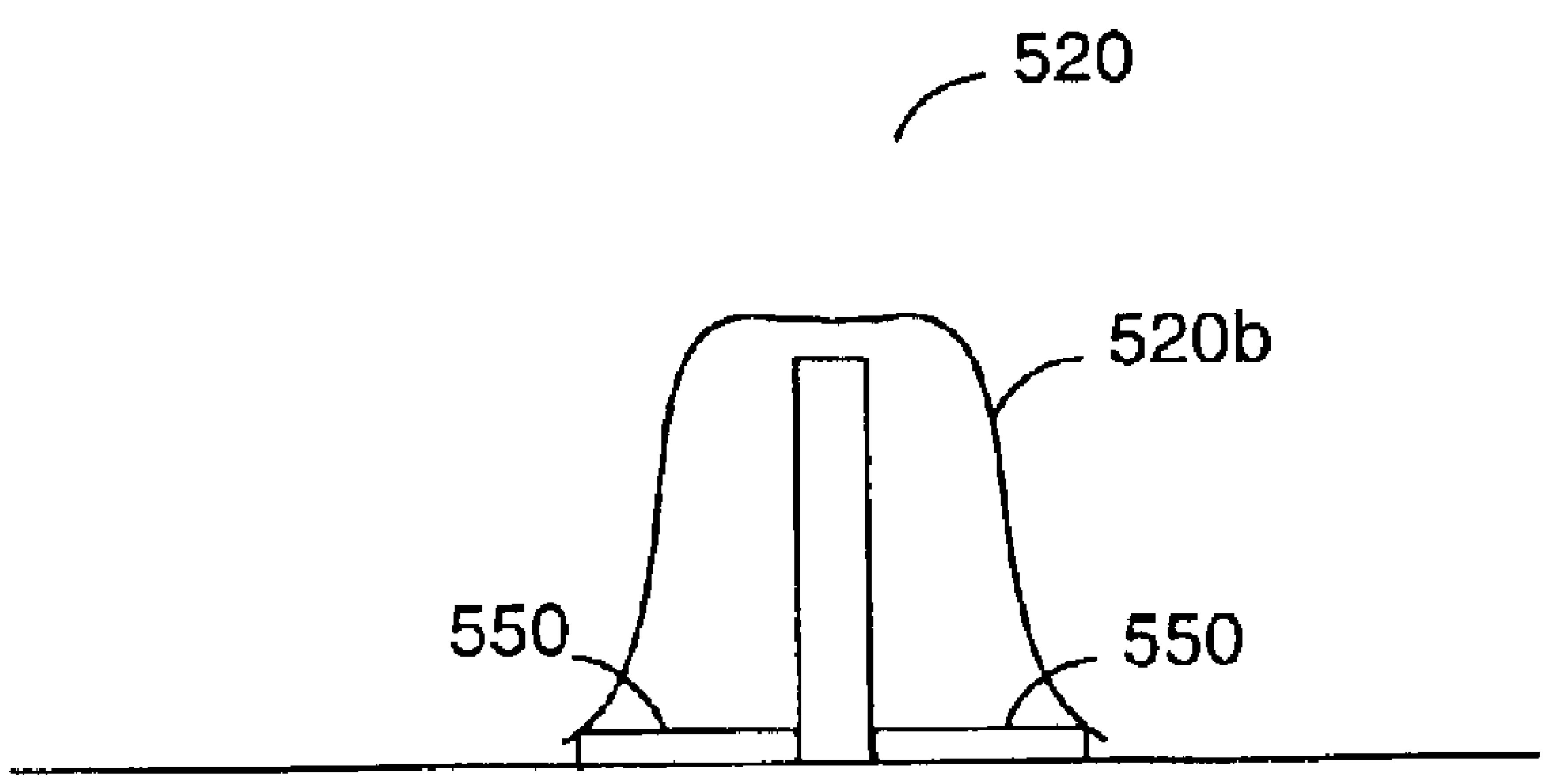

520
520b
550
550

FIG. 7D

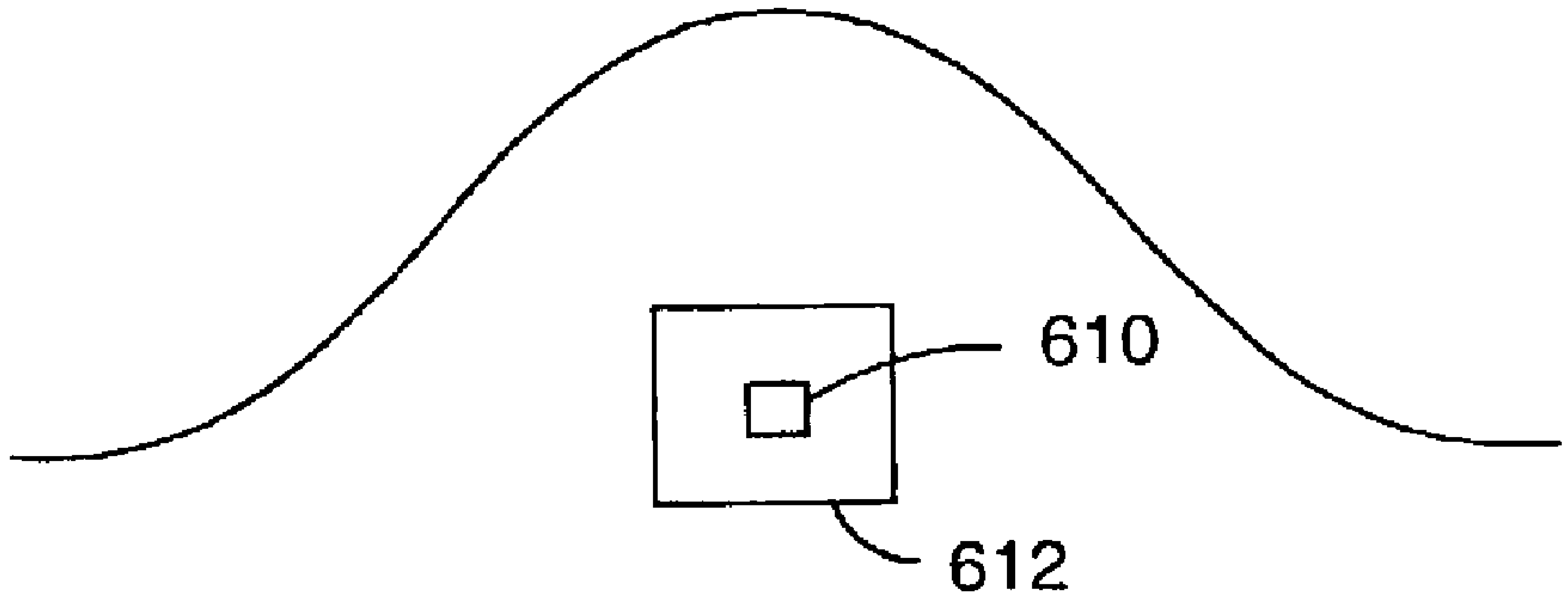


FIG. 8

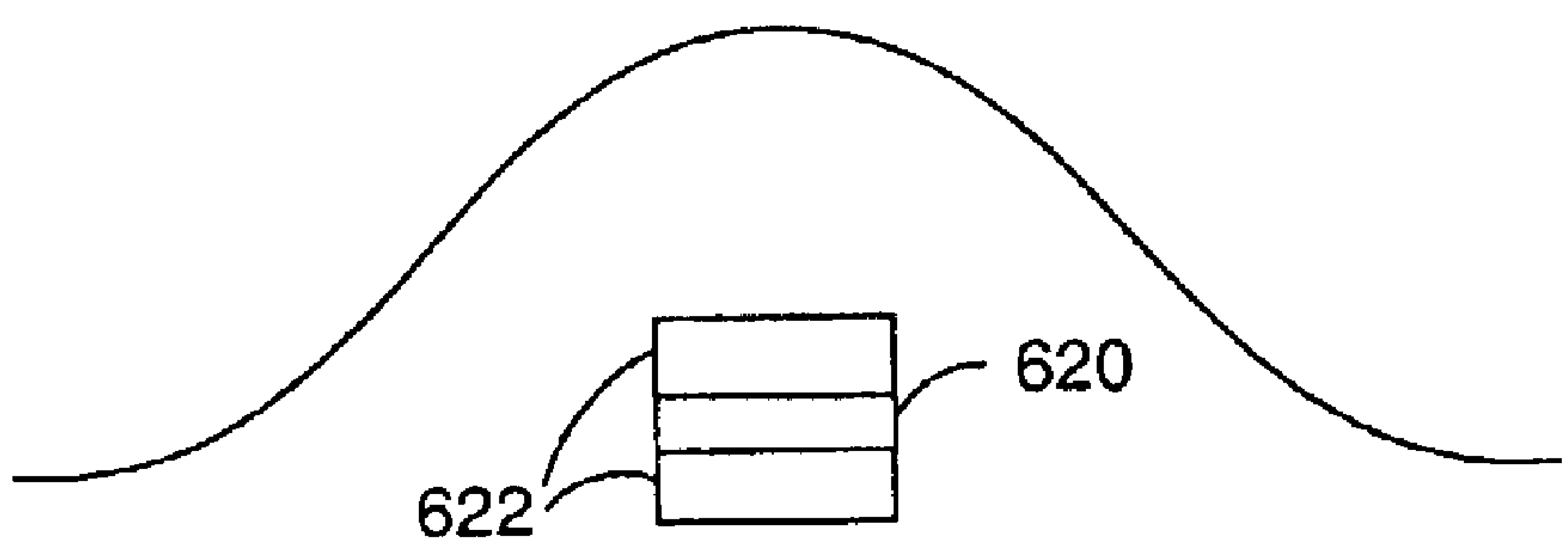


FIG. 9

THERMAL COMPENSATION OF WAVEGUIDES BY DUAL MATERIAL CORE HAVING POSITIVE THERMO-OPTIC COEFFICIENT INNER CORE

RELATED APPLICATIONS

This application is related to co-pending application, filed Jul. 2, 2002, entitled "THERMAL COMPENSATION OF WAVEGUIDES BY DUAL MATERIAL CORE HAVING NEGATIVE THERMO-OPTIC COEFFICIENT INNER CORE," and assigned to the Assignee of the present application.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The described invention relates to the field of optical circuits. In particular, the invention relates to thermal compensation in an optical waveguide.

2. Description of Related Art

Optical circuits include, but are not limited to, light sources, detectors and/or waveguides that provide such functions as splitting, coupling, combining, multiplexing, demultiplexing, and switching. Planar lightwave circuits (PLCs) are optical circuits that are manufactured and operate in the plane of a wafer. PLC technology is advantageous because it can be used to form many different types of optical devices, such as array waveguide grating (AWG) filters, optical add/drop (de)multiplexers, optical switches, monolithic, as well as hybrid opto-electronic integrated devices. Such devices formed with optical fibers would typically be much larger or would not be feasible at all. Further, PLC structures may be mass produced on a silicon wafer.

PLCs often have been based on silica-on-silicon (SOS) technology, but may alternatively be implemented using other technologies such as, but not limited to, silicon-on-insulator (SOI), polymer on silicon, and so forth.

Thermal compensation for some optical circuits, such as phase-sensitive optical circuits, is important as devices may be operated in locations where temperatures cannot be assured. In some cases, optical circuits are combined with temperature regulating equipment. However, these configurations may be less than ideal, since the devices are prone to failure if there is a power outage, and temperature regulating equipment may require a large amount of power which may not be desirable.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. **1A–1C** are schematic diagrams showing one embodiment of a cross-sectional view of a waveguide structure being modified to be thermally-compensating.

FIG. **2** is a flowchart showing one embodiment of a method for fabricating a thermally-compensating waveguide.

FIG. **3** is a schematic diagram showing one embodiment of an array waveguide grating (AWG) that makes use of the thermally-compensating waveguides.

FIG. **4** is a schematic diagram showing an embodiment of a PLC comprising an interferometric component that uses thermally-compensating waveguides in its coupler regions.

FIG. **5** is a graph illustrating the normalized mode field intensity in a cross section of a dual material waveguide.

FIG. **6** is a graph illustrating an aperture function for a dual material waveguide.

FIGS. **7A–7C** are schematic diagrams that illustrate another embodiment of a thermally compensated waveguide.

FIG. **7D** is a schematic diagram showing an enlargement of the core of the waveguide of FIGS. **7A–7C**.

FIG. **8** is a schematic diagram showing a cross sectional view of another embodiment of a waveguide having a dual material core.

FIG. **9** is a schematic diagram showing a cross section view of another embodiment of a waveguide having a dual material core.

DETAILED DESCRIPTION

A planar lightwave circuit comprises one or more waveguides that are thermally-compensating. The thermally-compensating waveguides comprise a cladding and a core that comprises two regions running lengthwise through the core. One region has a negative thermo-optic coefficient ("TOC"); the other region has a positive TOC.

FIG. **1A** is a schematic diagram showing one embodiment of a cross-sectional view of a waveguide structure **5**. In one embodiment, the structure is subsequently modified as described with respect to FIGS. **1B** and **1C** to be thermally-compensating.

As shown in FIG. **1A**, a layer of lower cladding **12** is typically deposited onto a substrate **10**. A waveguide core layer **20** is deposited over the lower cladding **12**, and an upper cladding **24** is deposited over the waveguide core layer **20**. In one example, the substrate **10** is silicon, the lower cladding **12** is SiO_2, the core layer **20** is SiO_2 doped with Germanium, and the upper cladding **24** is a borophosphosilicate glass (BPSG). In one embodiment, the upper cladding **24** may form a thin layer of approximately 1–2 microns covering the core.

FIG. **1B** is a schematic diagram showing one embodiment of a cross-section view of a waveguide after a trench **30** is created in the core layer **20**. In one embodiment, the trench **30** is formed to run along a length of the core of the waveguide. The trench may be formed by etching, ion beam milling, or other methods. In one embodiment, the trench has a depth of at least ⅔ of the depth of the core. However, the trench depth may extend down into the lower cladding **12**. The width of the trench is designed to be less than a wavelength of the optical signal to be propagated by the waveguide.

FIG. **1C** is a schematic diagram showing one embodiment of a cross-sectional view of FIG. **1B** after a layer of material **50** having a negative TOC has been deposited. The negative TOC material **50** fills the trench to form a negative TOC center region **40** of the core. In one embodiment, a polymer, such as silicone, poly(methylmethacrylate) ("PMMA"), or benzocyclobutene ("BCB"), is used. However, various other materials may alternatively be used.

When an optical signal propagates within the waveguide **5**, a first portion of the optical field of the optical signal propagates in the negative TOC region **40**, and a second portion of the optical field propagates in the positive TOC region **42** of the core. In one embodiment, the first portion of the optical field in the negative TOC region **40** is substantially surrounded by the second portion of the optical field in the positive TOC region **42**.

In one embodiment, the refractive index difference between the negative TOC region **40** and the positive TOC region **42** is large enough to allow filling over the negative TOC region **40** with a layer of the same material that serves as an upper cladding. The structure described provides good compensation with low loss over a wide temperature range, and allows for convenient fabrication.

FIG. **2** is a flowchart showing one embodiment of a method for fabricating a thermally-compensating waveguide. The flowchart starts at block **100**, and continues with block **110**, at which a core of the waveguide is formed over an appropriate substrate structure. In one embodiment, the core is formed on a SOS structure and comprises SiO_2 doped with Germanium having a cross-sectional area of approximately 6 microns by 6 microns. Other positive TOC materials may alternatively be used. The flowchart continues at block **120** at which a trench is created in the core. In one embodiment, the trench is approximately 1 micron wide and runs an entire length of the waveguide. At block **130**, a negative thermo-optic coefficient material is deposited into the trench. In one embodiment, an optical signal of approximately 1550 nm propagates within both the materials making up the core, having both positive and negative TOC regions. The flowchart ends at block **140**.

In an alternate embodiment, after the trench is filled with the negative TOC material, another material having a positive TOC may be used to cover the negative TOC material.

The effective index of propagation in the core will have a close to linear response to compensate for the thermal expansion of the substrate, and allows for thermal compensation up to a range of approximately 100° C. Additionally, the described waveguide structure may be used for curved waveguides. A bend radius of down to 10 mm is achievable with losses on the order of approximately 0.3 db/cm.

FIG. **3** is a schematic diagram showing one embodiment of an array waveguide grating (AWG) **200** that makes use of thermally-compensating waveguides. In one embodiment, the waveguides **210***a*–**210***x* are thermally-compensating as previously described, but the star couplers **220** and **222** and the input and output waveguides **230** and **232** are not thermally-compensated, allowing for easier alignment of the input and output waveguides **230** and **232** with other optical components.

FIG. **4** is a schematic diagram showing an embodiment of a PLC comprising an interferometric component **300** that uses thermally-compensating waveguides in coupler regions **310** and **312**. A temperature regulator **320** is used on a non-thermally-compensated waveguide portion to modify the phase of the optical signal. In one embodiment, an electrical component **350**, such as an optical-to-electrical converter and/or electrical-to-optical converter, is coupled to the thermally-compensated waveguide coupler **312**. One or more electrical connections **360** couple the electrical component **350** with power and other electrical signals. In an alternate embodiment, the phase modulation may be adjusted using other methods, such as mechanical.

In one embodiment, a temperature regulator **380** may be housed with a thermally-compensated optical circuit to keep the device within its thermally-compensating temperature range.

The thermally-compensating waveguides described compensate single mode waveguides independently. They may be used solely in a phase-sensitive portion or throughout an optical circuit.

A variety of different materials may be used for the thermal-compensation. For example, silicone has a TOC of −39×10−5/° C., PMMA has a TOC of −9×10−5/° C., and BPSG has a TOC of approximately 1.2×10−5/° C. The design of the trench may be altered to compensate for the use of various materials.

FIG. **5** is a graph illustrating the normalized mode field intensity in a cross section of a dual material waveguide. FIG. **6** is a graph illustrating an aperture function for a dual material waveguide. In one approximation, the waveguide materials are chosen to satisfy the following relation:

$$\int \Psi A_{PC}\Psi^{*}\cdot B_{PC}+\int \Psi A_{GC}\Psi^{*}\cdot B_{GC}+\int \Psi A_{CL}\Psi^{*}\cdot B_{CL}=-n\alpha_{substrate}$$

wherein

Ψ is the mode field intensity;

Ψ^* is the complex conjugate of the mode field intensity;

α is the linear thermal expansion coefficient, which is dominated by the substrate;

B is the thermo-optic coefficient;

n is the effective index of propagation; and

A is an aperture function having the value 1 within the material and 0 outside the material, and wherein the subscript PC indicates within the polymer core, GC indicates within the Ge Silica core, and CL indicates within the cladding.

For those skilled in the art, it is relatively straight-forward to include effects of strain and polarization to improve the accuracy of the modeling.

FIGS. **7A**–**7C** are schematic diagrams that illustrate another embodiment of a thermally compensated waveguide **505**. In this embodiment, the core **520** has a central portion that has a positive TOC and an outer portion that has a negative TOC.

FIG. **7A** shows a first core portion **520***a* having a positive TOC. The first core portion **520***a* forms a spike running the length of a waveguide. In one embodiment the first core portion is formed on a lower cladding **512** over a substrate **510**, similar to that of FIG. **1A**. The first core portion may be deposited and then etched to form a spike having the desired dimensions. Support structures **524** may be formed on the lower cladding **512** as long as they are far enough away from the core **520** to prevent light from leaking from the core to the support structure.

FIG. **7B** shows a negative TOC material deposited over the positive TOC first core portion **520***a* to form a second core portion **520***b*. The first core portion **520***a* and the second core portion **520***b* make up the core **520**. In one embodiment, the negative TOC core material is a polymer ("core polymer"). In one embodiment, the core polymer is formed by spinning accumulation. Alternatively, the core polymer may be applied by other lithography methods. In one embodiment, the core polymer has a refractive index of approximately 1.45 to 1.6.

FIG. **7C** shows a second negative TOC material deposited over the core **520** to form a cladding **530**. In one embodiment, the negative TOC material is a polymer ("cladding polymer") and has a refractive index approximately 0.01 to 0.05 less than that of the core polymer **520***b*. In one embodiment, the core polymer and the cladding polymer are related polymers.

FIG. **7D** is a schematic diagram showing an enlargement of the core **520** of the waveguide **505** of FIGS. **7A**–**7C**. In one embodiment, an undercladding **550** is deposited before applying the core polymer **520***a*. This provides an undercladding of polymer under the core, which creates an interface under the core that substantially matches the core/cladding interface on top of the core to provide better performance.

FIG. **8** is a schematic diagram showing a cross sectional view of another embodiment of a waveguide having a dual material core. In this embodiment, an inner core **610** is completely surrounded by an outer core **612**. In one case, the inner core has a negative TOC and the outer core has a positive TOC. In an alternate embodiment, the inner core has a positive TOC and the outer core has a negative TOC. The inner and outer cores may comprise polymer or other suitable materials.

FIG. **9** is a schematic diagram showing a cross section view of another embodiment of a waveguide having a dual material core. In this embodiment, an inner core **620** is sandwiched between an outer core **622**. The inner core, however, lies substantially in the plane of the substrate of the PLC, and will not have as good optical confinement for PLC's with significant bend radii compared to the structures previously described with respect to FIGS. **1**C and **7**C having inner cores in a plane substantially perpendicular to the plane of the substrate of the PLC.

Thus, an apparatus and method for making thermally-compensating planar lightwave circuit is disclosed. However, the specific embodiments and methods described herein are merely illustrative. For example, although the techniques for thermally compensating waveguides were described in terms of an SOS structure, the techniques are not limited to SOS structures. Numerous modifications in form and detail may be made without departing from the scope of the invention as claimed below. The invention is limited only by the scope of the appended claims.

What is claimed is:

1. A planar lightwave circuit comprising:

a first waveguide that is thermally-compensating, the first waveguide comprising

a cladding; and

a core substantially confined by the cladding, the core comprising first and second regions running lengthwise through the core, the first region having a positive thermo-optic coefficient, the second region having a negative thermo-optic coefficient, and wherein the first region runs substantially lengthwise through a central portion of the second region, wherein the planar lightwave circuit comprises an array waveguide grating.

2. The planar lightwave circuit of claim **1**, wherein the first region comprises a polymer.

3. The planar lightwave circuit of claim **2**, wherein the polymer comprises silicone, PMMA or BCB.

4. The planar lightwave circuit of claim **1**, wherein the second region comprises doped silica.

5. The planar lightwave circuit of claim **1**, wherein the first region forms an enclosed channel running through the central portion of the second region.

6. The planar lightwave circuit of claim **1**, wherein the planar lightwave circuit comprises an interferometer.

7. The planar lightwave circuit of claim **6**, wherein the planar lightwave circuit is a Mach Zehnder interferometer.

8. The planar lightwave circuit of claim **1**, wherein the planar lightwave circuit comprises a coupler.

9. The planar lightwave guide circuit of claim **1**, further comprising:

a second waveguide that is not thermally-compensating, the second waveguide comprising a core comprising a single material having a positive thermo-optic coefficient.

10. The planar lightwave circuit of claim **1**, wherein the first waveguide is thermally-compensating over a range of approximately 100° C.

11. The planar lightwave circuit of claim **10**, wherein the first waveguide has a bend radius down to greater than or equal to about 10 mm.

12. The planar lightwave circuit of claim **1**, wherein the first region extends into the second region by at least two-thirds.

13. The planar lightwave circuit of claim **1**, wherein the second region comprises a polymer.

14. The planar lightwave circuit of claim **1**, said core comprising an inner core and an outer core wherein the width of the inner core is approximately 1 micron or less.

15. A planar lightwave circuit comprising:

an electrical component, wherein the electrical component is an electrical-to-optical converter or sit optical-to-electrical converter; and

a waveguide coupled to the electrical component, the waveguide having a core capable of propagating an optical signal, the core comprising a first material and a second material, wherein the first material runs substantially through the center portion of the second material, and wherein the first material has a positive thermo-optic coefficient and the second material has a negative thermo-optic coefficient.

16. The planar lightwave circuit of claim **15**, wherein the first material splits the core into two portions along a length of the core.

17. The planar lightwave circuit of claim **16**, wherein the first material lies substantially in a plane parallel to a primary plane of the planar lightwave circuit.

18. The planar lightwave circuit of claim **16**, wherein the first material lies substantially in a plane perpendicular to a primary plane of the planar lightwave circuit.

19. The planar lightwave circuit of claim **15**, wherein the first material comprises polymer.

20. The planar lightwave circuit of claim **19**, wherein the second material comprises doped silica.

21. The planar lightwave circuit of claim **19**, wherein the second material comprises a polymer.

22. The planar lightwave circuit of claim **15**, wherein the electrical component is a temperature regulator.

23. A method of guiding an optical signal through a planar waveguide, wherein the optical signal has an optical field, the method comprising:

guiding a first portion of the optical filed in a first material;

guiding a second portion of the optical field in a second material, wherein the first material and the second material comprise a core of the planar waveguide, and wherein the first material has a negative thermo-optic coefficient and the second material has a positive thermo-optic coefficient, and wherein the second material is substantially surrounded by the first material.

24. The method of claim **23**, wherein the first portion of the optical field and the second portion of the optical field are substantially concentric.

25. The method of claim **23**, wherein the second portion of the optical field is guided within the first portion of the optical field.

* * * * *